MODELING ENERGETIC-CHARGED PARTICLES WITHIN THE EUROPA-JUPITER ENVIRONMENT

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MODELING ENERGETIC-CHARGED PARTICLES WITHIN THE EUROPA-JUPITER ENVIRONMENT

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LIST OF SYMBOLS AND ABBREVIATIONS

JEO:	Jupiter-Europa Orbiter
$\vec{B}$ or B-field:	Magnetic field
$\vec{E}$ or E-field:	Electric field
EJSM:	Europa-Jupiter System Mission
MHD:	Magnetohydrodynamic
nT:	nano-Tesla
$\vec{F}$:	Force

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Abstract

Europa, one of Jupiter's Galilean moons, is one of the few planetary bodies in our solar system thought to have the prospect of life. The Jupiter-Europa Orbiter (JEO), part of a new flagship mission, will be sent to the Jupiter System to study Europa. While in this environment, JEO will be exposed to energetic-charged particles, known as plasma. The radiation from these energetic-charged particles has the ability to disrupt the equipment on the orbiter and shorten its life-span. The long-term goal of this research is to model the Jupiter-Europa radiation environment in order to find shielded regions, areas where there are fewer energetic-charged particles, within the environment around Europa. The radiation environment will be modeled by combining magnetohydrodynamic (MHD) simulations and test particle trackers developed using FORTRAN. High energy test particles, driven by the Lorentz force law, will be launched and tracked through the environment of Europa that has been modeled using MHD simulations. This research develops a tool that can be used for tracking energetic-charged particle motion in a modeled environment. With further testing, these algorithms can be applied to locating these shielded regions which could help lengthen the life-span of the Jupiter-Europa Orbiter.

Chapter 1

Introduction

The Jupiter-Europa Orbiter (JEO) is part of the Europa Jupiter System Mission (EJSM) flagship mission to the deep-space environment of the Jupiter System. JEO's tasks will be to determine the extent of the sub-surface ocean, to study the ice shell-ocean interaction, to determine the chemistry and geology of Europa, and to understand Europa's role in Jupiter's environment (Davis 2011). The equipment and sensors on this mission will be exposed to Jupiter’s magnetic field and energetic-charged particles produced by the interactions between Jupiter’s magnetic field, satellites, and atmosphere as well as the solar wind from the Sun.

Once at Jupiter, the JEO will be exposed to energetic-charged particles and plasma located within the magnetic field of Jupiter and will have to deal with the constant bombardment and interaction with these particles. The concern from the engineering standpoint is to know the amount of radiation encountered at Europa, so that JEO and its sensors can be built to withstand the harsh environment around Europa. This project focuses on modeling the environment to locate shielded regions, areas where there are fewer energetic-charged particles, around Europa. It is important to locate these shielded regions because taking advantage of them in spacecraft orbit planning will help to cut down on the amount of energetic-charged particles JEO will be exposed to during that portion of the mission. Decreasing this exposure will allow the sensors on the JEO to last longer so more data can be collected for a variety of studies. Assessment of past and current spacecraft operations is important for developing better ways to protect future spacecraft from harsh environments. The next section discusses a few of the problems that the Galileo spacecraft encountered while in orbit around Jupiter.

Effect of radiation on spacecraft

Spacecraft instrumentation can be affected by radiation from sources within Jupiter's magnetic field or from radiation from the Sun. These sources include: (1) increased solar activity which cause solar flares and Coronal Mass Ejections (CMEs) and (2) events within Jupiter's magnetic field, such as the volcanic eruptions on Io and its plasma torus (Fieseler 2002). Jupiter's magnetic field creates "noise" within collected data which can easily be corrected. Problems arise with a spacecraft's exposure to sporadic events and energetic-charged particles produced by the surrounding environment. These events can temporarily disrupt or cause permanent damage to sensors and other devices on spacecraft. Fieseler (2002) assessed a variety of equipment disruptions, resets, and failures on the Galileo spacecraft. One key issue is making sure that the spacecraft stays properly referenced within the environment. For example, Galileo's Star Scanner misinterpreted Io's volcanic eruptions as star light from a nearby reference star because they had similar detectable properties (Fieseler 2002). If a spacecraft loses its point of reference to the environment without a back-up system, the entire mission could be lost. The increased radiation within this environment is of great concern and it is important that proper steps are taken to decrease exposure to the energetic-charged particles. Aluminum protective shielding, strategic equipment resets, and spacecraft angling help to decrease radiation exposure when in the Europa-Jupiter environment, but another useful strategy is to locate shielded regions around Europa. The environment around Europa is impacted by a variety of factors which will be discussed thoroughly in the next section.

Radiation environment around Europa

The success of JEO's mission depends on what we already know about Europa and its surroundings. In order to determine exactly where these shielded regions are located, we have to understand the Europa-Jupiter interaction and its radiation environment. Europa's induced dipole magnetic field, its near-surface and extended atmospheres, and its ionosphere all play important roles in governing Europa's interaction with Jupiter's magnetic field, and in turn affect the radiation environment around Europa.

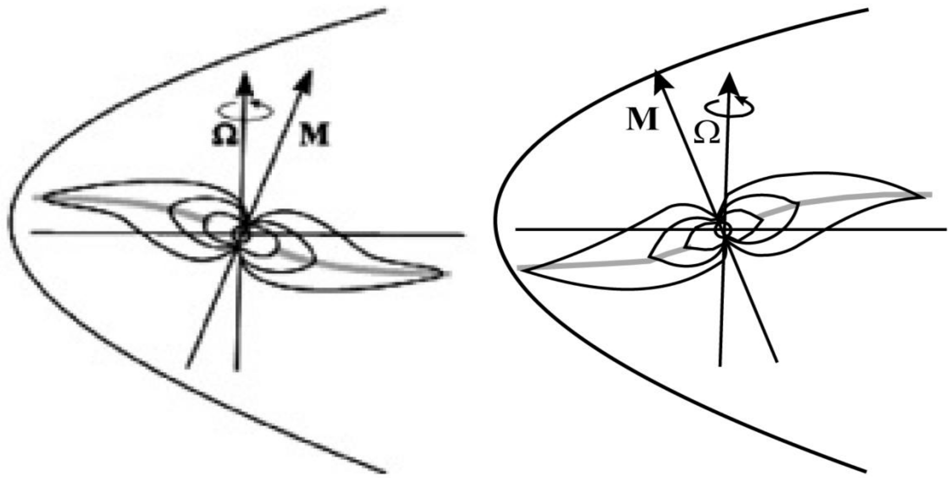


Figure 1 This visual represents Jupiter's magnetic field where Jupiter is located at the center of the axes, Ω is the rotational axis of Jupiter, and M is the axis of Jupiter's magnetic moment, which is approximately a dipole offset by 10° from the rotational axis. The gray line running through the magnetic field lines is the plasma sheet; an area of higher density plasma that is co-rotating with Jupiter and its magnetic field (Paty 2006).

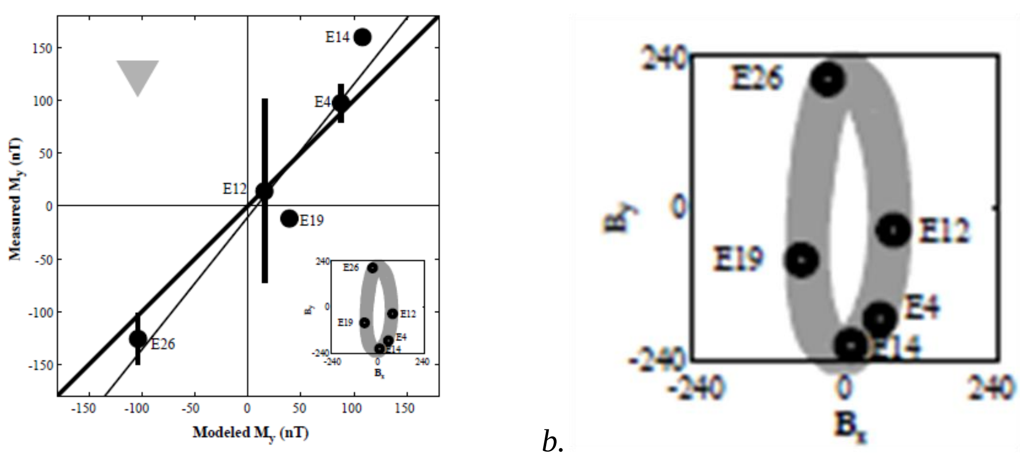
a. Europa's induced dipole magnetic field

Galileo's fly-bys of Europa show evidence of a subsurface ocean at Europa (Kivelson 2000). Previous studies implicate that this subsurface ocean affects Europa's interaction with Jupiter's magnetic field. Kivelson (2000) concluded that Europa's subsurface ocean is an electrically conducting layer that creates an induced dipole magnetic field around Europa.

Galileo fly-bys measured the magnetic field at Europa in the Cartesian coordinate system (x, y, and z). The x-axis is in the direction of the plasma flow. The y-axis is in the direction of Jupiter in its orbital plane at Europa. The z-axis is perpendicular to the orbital plane and roughly anti-parallel to Jupiter's magnetic field at Europa. From these fly-bys, the location of Europa with respect to the plasma sheet of Jupiter can be deduced from the ingress and egress measurements of the magnetic field in the y-direction. An observed positive magnetic field (B_y) means that Europa is below the plasma sheet; Europa is above the plasma sheet if B_y is negative; and a B_y observation of zero indicates that Europa is within the plasma sheet. The magnetic field observations allow us to locate the position of Europa at that point in time. Table 1 and Figure 2 show examples of these observations. We can assess the radiation dosage and locate the shielded regions in the environment around Europa by using observations of the strength and orientation of Jupiter's magnetic field to constrain the local plasma dynamic conditions.

Magnetic field strength at <2000 km from Europa surface					
Fly-by	Date	Bx (nT)	By (nT)	Bz (nT)	|Btotal| (nT)
E4	12/19/1996	60	-175	-410	450
E12	12/16/1997	90	50	-480	490
E14	3/29/1998	12.5	-215	-405	455
E26	1/3/2000	-20	205	-380	430

Table 1 The following values are approximations of four of the magnetic field observations taken by the Galileo spacecraft. The values were approximated from figures 1, 2, and 4 in Kivelson 2000 (nT is a nano-Tesla).



a. b.

Figure 2 a. This graph represents the comparison between the measured and modeled magnetic field along the y-axis fly-bys of the Galileo spacecraft with respect to the plasma sheet. b. The small box, zoomed-in on at the right, indicates the location of the fly-bys with respect to the y-direction and plasma sheet where a zero magnetic field is within the plasma sheet (Kivelson 2000).

b. Europa's atmospheric composition and ionosphere

Europa's atmosphere and ionosphere contribute to the radiation environment around Europa. The main composition of the near-surface atmosphere of Europa is O_2. Europa's extended atmosphere is composed of Oxygen and Sulfur ions of varying charge states (S^+, S^{++}, S^{+++}, O^+, O^{++}). S^{++} and O^+ dominate the region around Europa (Bagenal 1994). The ratio between Oxygen and Sulfur ions helps us to define the upstream conditions for our study. The upstream conditions are parameters that are in the direction of the plasma flow and the rotation of Jupiter.

Europa's ionosphere defines the boundary between the plasma flow and Europa's atmosphere. The ionosphere has a plasma scale height of 240 ± 40 km for the region from the surface to 300 km and a plasma scale height of 440 ± 60 km above 300 km (Kliore 1997). In these regions, temperatures range from about 340 K to 600 K. These temperatures are much greater than that observed at the surface of Europa; therefore, heating is likely due to a source in Jupiter's magnetosphere (Kliore 1997). This area of increased temperatures is part of the radiation environment we are concerned with modeling in order to locate the shielded regions.

c. Radiation dosage at Europa

For this part of the discussion we are concerned with the energetic-charged particles within the upstream plasma flow in Jupiter's magnetic field. The amount of charged particles that Europa absorbs is dependent on their electron temperatures and the latitude at which they collide with Europa. This temperature is measured in electron-volts (eV). The energetic-charged particles move within the plasma flow, and their speeds vary depending on their temperatures.

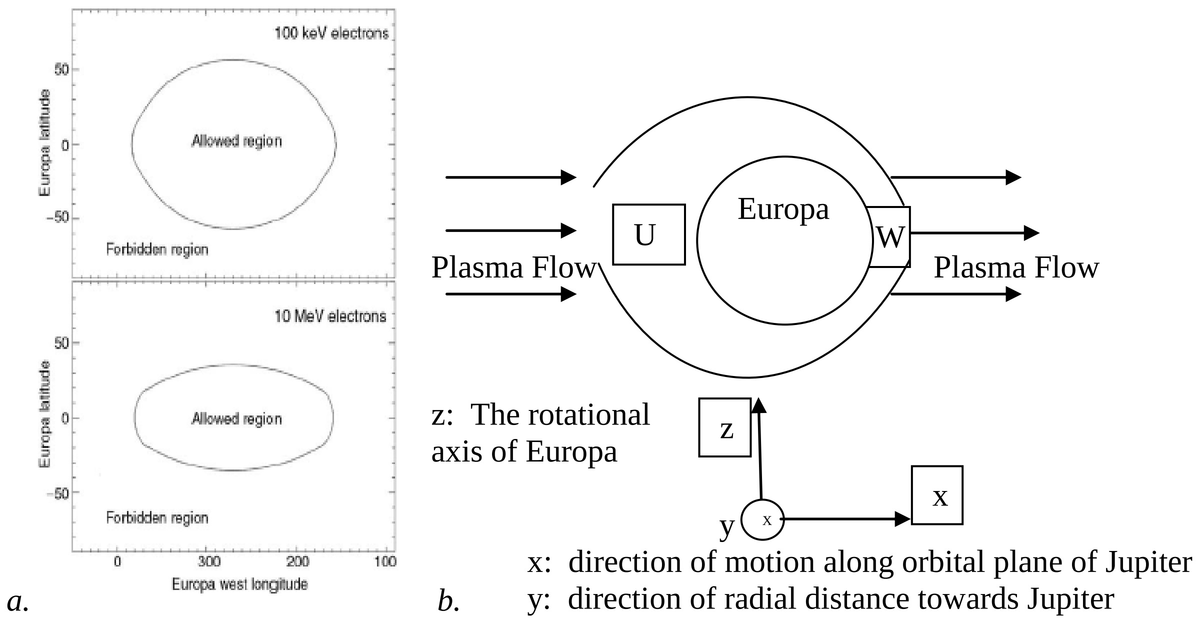


Figure 3 a. The graphs represent the allowed and forbidden positions along the trailing hemisphere of Europa for electrons of 100 keV and 10 MeV. This figure shows how the increase in temperature decreases the size of the allowed regions for these electrons (Paranicas 2007). *b*. This diagram represents Europa in motion around Jupiter. “U” indicates the upstream flow side (trailing edge) of Europa and “W” indicates the wake side (leading edge) of Europa. The plasma flow is in the direction of Europa’s orbital motion around Jupiter. The curves around Europa represent the deflection of the plasma flow around Europa. This figure is not drawn to scale.

These energetic-charged particles within the plasma flow consist of ions and electrons. The ions drift in the same direction and are faster than the plasma flow, while the electrons drift in the opposite direction and are slower than the plasma flow. The highly energetic electrons have the ability to disrupt spacecraft measurements (Paranicas 2007). It is important to determine the locations on and around Europa that are hit by these electrons. Figure 3a shows the regions where these electrons have access to Europa’s near-surface atmosphere. For Paranicas’s model, calculations are performed for a hypothetical spacecraft that is located at 100 km from Europa’s surface. The Paranicas model shows the regions and conditions that a spacecraft should avoid when in an environment similar to that of Jupiter and Europa. The graphs denote the size of these regions at 100 keV and 10 MeV for the trailing edge of Europa. Figure 3b shows a diagram that provides a representation of Europa’s orientation in the Jupiter environment and the plasma flow. The trailing edge of Europa is indicated by the “U” region in Figure 3b. At a temperature greater than 25 MeV, these electrons move in the direction opposite to the plasma flow and can penetrate regions on the leading edge of Europa (Paranicas 2007).

The most recent data and observations were made by fly-bys done by the Galileo spacecraft during the 1990s and early 2000s and have also come from the Hubble Space Telescope (HST). Much of this data is available to the public on the Planetary Data System (PDS).

Chapter 2

Methodology

We used the data from the PDS to provide observationally derived boundary conditions for the Magnetohydrodynamic (MHD) simulations. We created a MHD simulation of the Jupiter-Europa environment and sent high energy test particles through this environment in a variety of cases. The model created to launch and track the high energy test particles through a given environment can be used as a tool to help find the shielded regions around Europa in the Jupiter system. Our model tracks the motion of individual high energy test particles through the environment generated by the MHD model. The resulting trajectories of many test particles can then be used to statistically determine the radiation dosages at various locations.

In order to create algorithms that would track the motion of these energetic-charged particles, we used simplified cases of test particle motion with known analytical solutions to establish and validate the finite difference method and time stepping algorithm.

Finite difference methods for solving differential equations

Our algorithm calculated and tracked the position ($\vec{x}$), velocity ($\vec{v}$), and acceleration ($\vec{a}$) of the test particle. The equations of motion we based our study off of were as follows:

$$\vec{x}_f = \vec{x}_i + \vec{v}_i \Delta t + \frac{1}{2}\vec{a}_i \Delta t^2 \qquad (1)$$

$$\vec{v}_f = \vec{v}_i + \vec{a}_i \Delta t \qquad (2)$$

$$\vec{a} = \frac{\vec{F}}{m} \qquad (3)$$

where *i* and *f* represent the initial and final values of the parameters, Δt is the time step, and *m* is mass. Next, we converted equations 1, 2, and 3 into differential form and used the Lorentz Force Law ($\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$) to push the test particles in our algorithm:

$$\vec{x}_f = \vec{x}_i + \vec{v}_i \Delta t + \frac{1}{2}\frac{d\vec{v}_i}{dt}\Delta t^2 \quad (4)$$

$$\vec{v}_f = \vec{v}_i + \frac{d\vec{v}_i}{dt}\Delta t \quad (5)$$

$$\vec{a} = \frac{\vec{F}}{m} = \frac{d\vec{v}_f}{dt} = \frac{q(\vec{E}+\vec{v}_i\times\vec{B})}{m} \quad (6)$$

To examine the time stepping methods we calculated the outcomes of these three equations of motions using two finite difference schemes and two different assumptions for determining the time step size.

Time stepping methods and step size

Before sending the energetic-charged test particles through any sort of model environment, we had to first determine which finite difference method to use. We evaluated first and second order difference methods on the Lorentz Force Law and the equations of motion to determine which method was most appropriate for this system of equations.

We also evaluated two methods for determining the time step increment; the Courant condition and the gyroperiod equation. The Courant condition time step is a method in which there is a set large distance that is divided into smaller distances via a grid. This grid distance is then divided by the initial velocity at that time step and multiplied by an increment value between 0 and 1. The equation for this time step is:

$$\Delta t = increment * \frac{distance}{v_i} \quad (7)$$

where Δt is the time step in seconds. This condition indicates that a particle with velocity, v_i, will not travel farther than 1 grid distance in time, Δt. The second method used to determine the time step was the gyroperiod equation:

$$\Delta t = increment * \frac{2\pi}{{qB_z}/{m}} \quad (8)$$

where q is the charge of the particle, B_z is the magnetic field in the z-direction, and m is the mass of the particle. Once again, the increment is set to lie between 0 and 1 to ensure that for a given time, Δt , the particle completes less than 1 full gyration. The Courant condition and gyroperiod equation time stepping methods were tested using first and second order difference equations.

First order methods

The first order method we used to determine the values of the position, velocity, and acceleration of the test particle was the forward Euler method. The forward Euler method was applied to the derivatives of the position and velocity equations:

$$\frac{\vec{x}_{n+1}-\vec{x}_n}{\Delta t} = \frac{d\vec{x}}{dt} \quad (9)$$

$$\frac{\vec{v}_{n+1}-\vec{v}_n}{\Delta t} = \frac{d\vec{v}}{dt} \quad (10)$$

Equations 9 and 10 show the format of this first order method, where n represents an integer from 1 to a set parameter value. The parameter values used to test the time stepping methods were 50, 500, and 5000 steps. Equations 9 and 10 were modified and combined with equations 4 and 5, respectively to solve for their values at the next time step, n+1:

$$\vec{x}_{n+1} = \vec{x}_n + \vec{v}_n \Delta t + \frac{1}{2}\frac{d\vec{v}_n}{dt}\Delta t^2 \quad (11)$$

$$\vec{v}_{n+1} = \vec{v}_n + \frac{d\vec{v}_n}{dt}\Delta t \quad (12)$$

$$\frac{d\vec{v}_{n+1}}{dt} = \vec{a}_{n+1} = \frac{\vec{F}}{m} = \frac{q\left(\vec{E}+\vec{v}_n\times\vec{B}\right)}{m} \quad (13)$$

Equation 6 is reintroduced in the form of equation 13. The value of the acceleration needed to be recalculated at each time step in order to calculate the new positions and velocities.

Second order methods

The second order method we used to determine the values of the position, velocity, and acceleration of the test particle was the Runge-Kutta method. The Runge-Kutta method requires a two-step process to compute the new values of the position and velocity. The first step (k1) uses the forward Euler method to obtain the initial value points. The second step (k2) computes the midpoint of the interval and uses it to obtain the next value. The Runge-Kutta method in its most generic form is:

$$k1 = f(t_n, y_n) \tag{14}$$

$$k2 = f\left(t_n + \frac{1}{2}h, y_n + \frac{1}{2}hk_1\right) \tag{15}$$

where the function ($f(t_n, y_n)$) is the derivative of the parameter, t_n represents the time, y_n is the parameter (position or velocity), and h is the time step Δt. The second order Runge-Kutta and first order forward Euler methods were used to compute the numerical solution of the charged particle motion and were then evaluated for accuracy against the known analytical solution for a simple case.

Particle Motion

As mentioned previously, the Lorentz Force Law ($\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$) was used to push the test particles. We used FORTRAN code to model the environment and to check the numerical solution of the gyromotion by calculating the position, velocity, and acceleration of the test particles through this environment.

The three energetic-charged particles of interest are hydrogen, oxygen, and sulfur. Each of these particles has a different gyroradius. The analytical solution of the gyromotion is the gyroradius represented by the following equation: $r_g = \frac{mv_\perp}{|q|B_z}$, where $v_\perp$ is the velocity perpendicular to the magnetic field in the z-direction. We then compared the analytical and numerical solutions for the test particles for a variety of different cases.

- Case 1: $\vec{E} = 0, \vec{B} = \langle 0,0,B_z \rangle, \vec{v} = \langle v_x, 0,0 \rangle$
- Case 2: $\vec{E} = 0, \vec{B} = \langle 0,0,B_z \rangle, \vec{v} = \langle v_x, v_y, v_z \rangle$
- Case 3: $\vec{E} = \langle E_x, 0,0 \rangle, \vec{B} = \langle 0,0,B_z \rangle, \vec{v} = \langle v_x, v_y, v_z \rangle$

The particles were tested in these different cases into order to (1) observe how the initial conditions and environment affect the gyromotion of the different energetic-charged particles and (2) to assess the accuracy of the finite difference approaches. Once the correct motion was achieved, the particles were placed in a more complex environment.

Setup of boundary conditions of MHD model

The complex environment includes particle densities, velocities, and magnetic fields determined by an MHD simulation. The boundary conditions for the MHD model come from Galileo spacecraft observations and can be found on the Planetary Data System (PDS). This complex environment was created to test for the changes in magnetic field strength and orientation during Europa's orbital path around Jupiter.

Cases and parameters

To begin this part of our study, we needed to set up the model environment. First, we ran magnetohydrodynamic (MHD) simulations for the Jupiter magnetic field and Europa interactions. This was done for three separate cases which were quantitatively constrained by observational data:

1. Europa located below the plasma sheet.
2. Europa located above the plasma sheet.
3. Europa located within the plasma sheet.

We know how the plasma parameters vary in each case from the observations made by the Galileo spacecraft, so we used them as boundary conditions for the simulations. The parameters are as follows: the magnetic field in the x, y, and z direction (B_x, B_y, B_z), the total magnitude of the magnetic field ($|\vec{B}|$), the plasma density (ρ), the velocity (v), and the temperature (T). The Europa-Jupiter environment is a dynamic system, and we are trying to understand the interactions of the energetic-charged test particles with the electric and magnetic fields created by these boundary conditions.

Model environment

We extracted the strength and orientation of the electric ($\vec{E}$) and magnetic ($\vec{B}$) fields from the MHD simulations. Once the model environment was created, we further developed an energetic-charged particle pusher and tracker code that used the $\vec{E}$ and $\vec{B}$ fields as background fields.

The goal was to then send test particles through the modeled environment of these three cases. This would have to be performed several times at different initial starting points in order to study the spatial distributions of energetic-charged particles around Europa. Upon completing this suite of particle tracking models, we should be able to determine the distribution of the energetic particles around Europa, to define its radiation environment, to and locate its shielded regions. However, in order to correlate the location of the energetic-charged test particles to the magnetic field strengths and orientations, we first had to develop a system for extrapolating the $\vec{E}$ and $\vec{B}$ values from the MHD simulation grid to the exact location of the test particles.

Gridding

The location of the test particles can be mapped on the grid provided by the MHD simulation. The grid represents the location of the background electric and magnetic field information in the Europa-Jupiter environment as modeled by the MHD simulation. In order to determine the strength of the $\vec{E}$ and $\vec{B}$ values at the location of the test particle in the grid, we used a weighted average equation for a three-dimensional system:

$$weighted\ average = \frac{\sum_{i=1}^{N=3} d_i \cdot p_i}{\sum_{i=1}^{N=3} d_i} \qquad (16)$$

where p_i is the value of a point in x, y, or z direction and d_i is the weight of that point. With the weighted average, we pinpointed the nearest neighbors on the grid relative to the location of the test particle. We then can use the location to determine the strength of the magnetic field that the particle encounters.

Chapter 3

Results

As the energetic-charged particles move through the Europa-Jupiter environment, their gyromotions are dependent on the conditions they encounter. The environment that these particles inhabit is very complex due to varying electric and magnetic fields. The code created for this study was used to obtain the motion of the energetic-charged test particles in a modeled Europa-Jupiter environment.

Approach

As stated previously in the methodology section, the analysis of the gyromotion was done for a variety of simplified cases. I will discuss the results from three of these cases. The initial values for these cases are shown below:

Initial values for simplified cases of particle motions			
Case	Electric field (N/C)	Magnetic field (nT)	Velocity (m/s)
1	$\vec{E} = \langle 0,0,0 \rangle$	$\vec{B} = \langle 0,0,B_z \rangle$	$\vec{v} = \langle v_x, 0,0 \rangle$
2	$\vec{E} = \langle 0,0,0 \rangle$	$\vec{B} = \langle 0,0,B_z \rangle$	$\vec{v} = \langle v_x, v_y, v_z \rangle$
3	$\vec{E} = \langle E_x, 0,0 \rangle$	$\vec{B} = \langle 0,0,B_z \rangle$	$\vec{v} = \langle v_x, v_y, v_z \rangle$

Table 2 These initial values are the generic starting points in vector form for the parameters that were used for the Lorentz particle tracker code

The numerical solutions for the gyroradius of the energetic-charged particles were calculated using the initial conditions generalized above and the equations of motion. The equations of motion track the position ($\vec{x}$), velocity ($\vec{v}$), and acceleration $\left(\frac{d\vec{v}}{dt} = \vec{a}\right)$ of the particle.

The acceleration equation is based off the Lorentz force law ($\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$). These equations were used in the particle tracker code. The particle tracker code compiled the data into separate files containing the updated positions, velocities, accelerations, and time steps of the energetic-charged test particle. The position and time period files were used in MATLAB scripts that output the graphs of the numerical solution verse the analytical solution of the gyroradius for the test particle. Case 1 was used as a testing ground for the development of the Lorentz particle tracker code. The results obtained for the initial values of the first case for a hydrogen ion will be described below.

Development and testing of Case 1

Case 1 provided the simplest case study for particle motion to develop the particle tracker code. The initial velocity (v_x) of the hydrogen ion used for case 1 was 85000 m/s. This value was obtained from Neubauer (1998) and represents the velocity of the incident flow at Europa. The strength of the constant magnetic field (B_z) for case 1 was an arbitrary value chosen to be 400 nT based off calculations done for the magnetic field strength of Jupiter's magnetic field at Europa. In order to validate which time stepping sequence was best, we compared the changes in the x and y position for the numerical and the analytical solution of the gyroradius (r_g) with respect to time. The position for case 1 did not change in the z direction. The Courant condition and fraction of a gyroperiod time stepping sequences were used to determine the numerical solutions of the gyroradius. These two time stepping sequences were then tested to determine which method provided the best fit for the motion of the test particles.

Analysis of time stepping methods

The Courant condition and fraction of a gyroperiod time stepping sequences were tested using a 1st order forward Euler method and a 2nd order Runge-Kutta method. The first and second order finite difference methods were used to calculate the positions in the x and y directions with respect to time and were graphically compared to the analytic solution. When comparing the numerical solution to the analytical solution of the gyroradius, I changed the size of the time increment (0.1, 0.01, and 0.001) and number of steps for each run (50, 500, and 5000) in order to assess error propagation of the different sequences and finite difference methods.

The resulting figures show the numerical solution of the gyroradius getting closer to the analytical solution as the size of the increment decreased. Figure 4 shows the numerical solution which uses the 1st order forward Euler method and the Courant condition as the time stepping method. Figure 5 shows the numerical solution which used the 1st order forward Euler for the fraction of a gyroperiod equation as the time stepping method. However, as you see from figures 4 and 5, there was an error that propagated with increasing amplitude as time elapsed for 1st order methods.

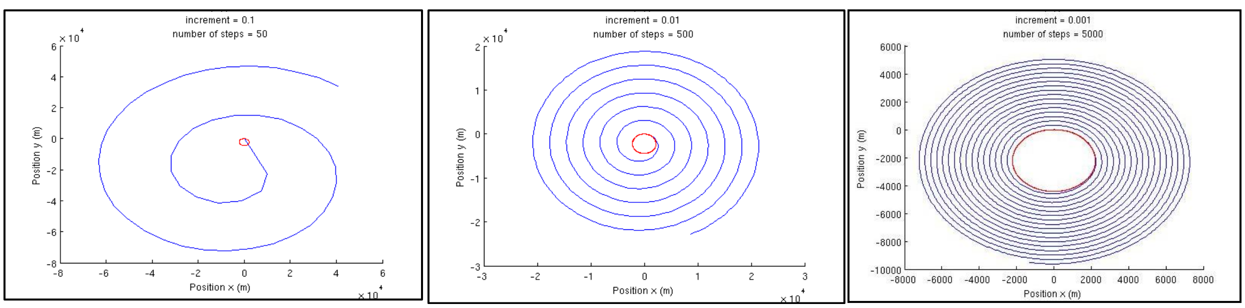


Figure 4 displays the stepping increment and number of steps taken for each of the numerical solutions based off the Courant condition. The red colored line represents the gyroradius of the hydrogen ion in an environment with a 400 nT magnetic field and the blue line represents the numerical solutions of the gyromotion in this model environment.

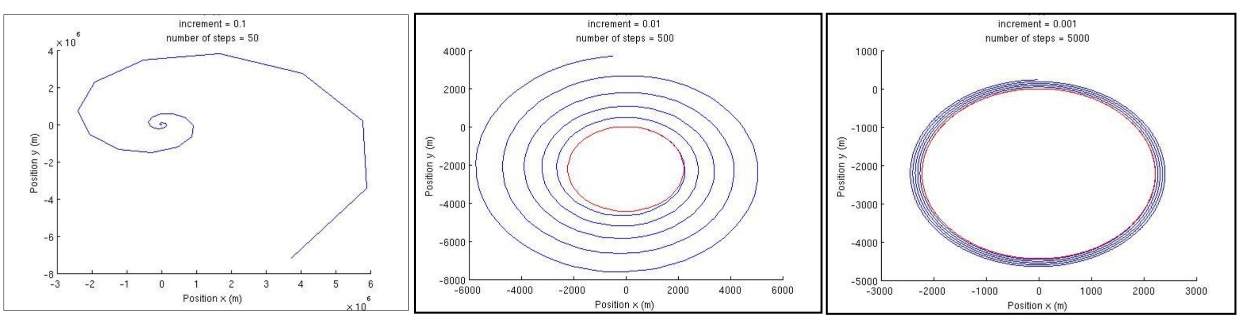


Figure 5 displays the stepping increment and number of steps taken for each of the numerical solutions based off the gyroperiod equation. The red colored line represents the analytical solution of the gyroradius of the hydrogen ion in an environment with a 400 nT magnetic field. The blue line represents the numerical solutions of the gyromotion in this model environment.

In order to decrease this error, we reevaluated the time stepping methods using a 2nd order Runge-Kutta method. Figure 6 shows the numerical solution of gyroradius which uses a 2nd order Runge-Kutta and the gyroperiod equation as the time stepping method. The error is not easily distinguished from the the numerical solutions of the 2nd order Runge-Kutta gyroperiod equation using the 0.01 increment or 0.001 increment.

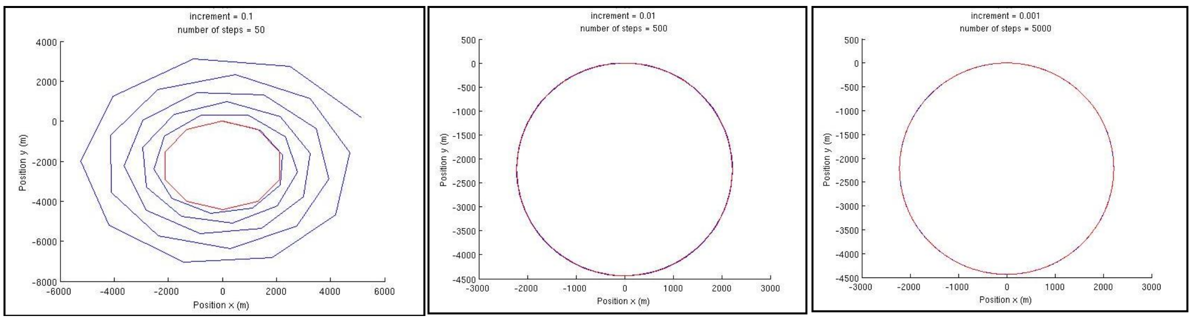


Figure 6 is a top-down view of the 2nd order Runge-Kutta method based off the gyroperiod equation. It displays the stepping increment and number of steps taken for each of the numerical solutions. The red lines represent the gyromotion of the hydrogen ion in an environment with a 400 nT magnetic field. The blue lines represent the numerical solutions of the gyromotion in this model environment.

Figure 7 compares the error, with respect to time, of the numerical solutions using the first order forward Euler method to the second order Runge-Kutta method numerical solutions for the fraction of a gyroperiod. The Courant condition time stepping sequence was too difficult to graph because the test particle travels a set distance over varying times not comparable to the gyroperiod time stepping sequence. As the number of steps increased and size of increment decreased, the test particle took longer to travel that set distance. For the fraction of a gyroperiod using the 1st order Euler method, there was an exponential increase in error with time. For the 2nd order Runge-Kutta method, the error was close to zero as time continued. The error propagation for the increments of 0.01 and 0.001 were small and difficult to graph and are therefore not shown in Figure 7.

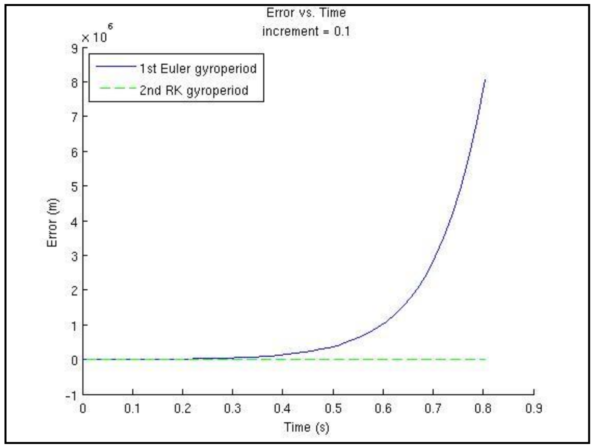


Figure 7 represents the error propagation of the numerical solution for the fraction of a gyroperiod time stepping sequence using the two different finite difference methods.

From the analysis of case 1, we found that the1st order methods were insufficient for approximating the gyroradius due to the error that propagated with increasing amplitude as time continues. The 2nd order Runge-Kutta method gives us a better approximation of the gyroradius. Therefore, we will want to use the 2nd order Runge-Kutta method to track the motion of the energetic-charged particles in the complex model environment. We also determined that the fraction of a gyroperiod time stepping sequence does a better job at approximating the gyroradius of the hydrogen ion test particle than the Courant condition time stepping sequence. In summary, we proceeded by applying the 2nd order Runge-Kutta method for fraction of a gyroperiod as our time stepping sequence in the more complex cases.

Application of particle tracker code

The developed Lorentz particle tracker code was applied to more complex background electric and magnetic fields. The code used an increment of 0.01 and 500 steps to calculate the numerical solution of the gyromotion. Two of these more complex configurations are represented by case 2 and 3, mentioned in the methodology section. Case 2 and 3 have the same initial velocity vector of $\vec{v} = \langle 50000{,}35000{,}15000 \rangle$ m/s and a magnetic field in the z-direction similar to that of case 1.

Case 2

For case 2, the initial conditions were a magnetic field in the z-direction, velocities in the x, y, and z directions, and no electric field. Figure 8 shows the resulting gyromotion for this case of Lorentz particle tracker code. The hydrogen ion test particle is gyrating in all 3 dimensions of space with time increasing the z direction. This is the type of gyromotion we expect to see from the given initial parameters.

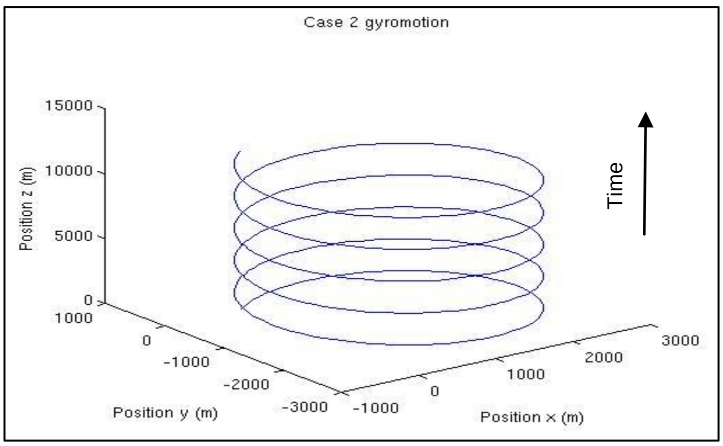


Figure 8 represents the gyromotion of a hydrogen ion in the x, y, and z directions with an given initial velocity vector using the 2nd order Runge-Kutta method which calculates values every 500 steps at a 0.01 time step increment.

Case 3

For case 3, an electric field in the x direction was introduced. With the addition of an electric field in combination with the magnetic field, E cross B drift ($\vec{E} \times \vec{B}$) occurs. The electric field is in the positive x direction and magnetic field is in positive z direction, so the drift occurs in the negative y direction. This type of gyromotion is displayed in Figure 9 with the blue line gyrating in the negative x direction. The result from this case shows that our code is working properly to incorporate varying electric field parameters.

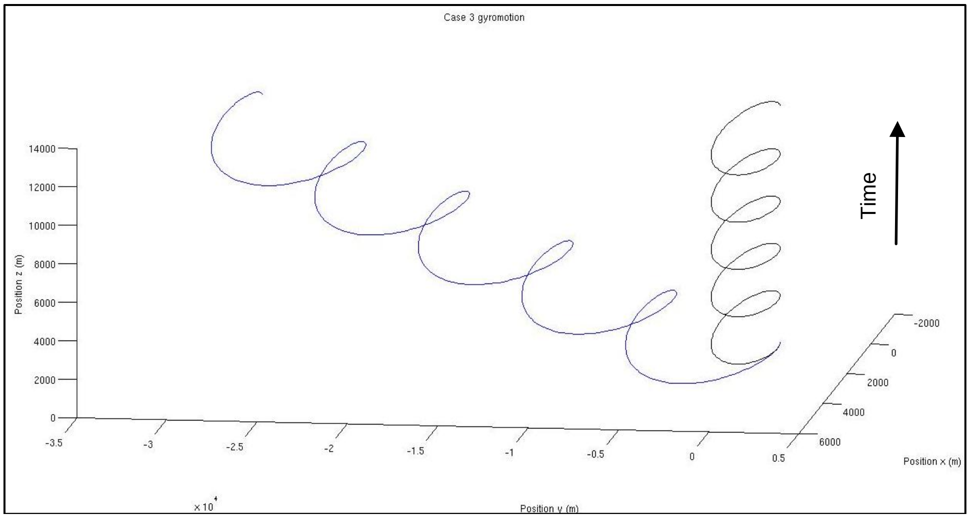


Figure 9 represents the motion of a gyrating particle from case 3. The black spiral represents the gyromotion obtained from case 2. The blue spiral represents the gyromotion of the hydrogen ion with the addition of the an electric field in the x direction.

For each different case, we changed the initial parameters slightly and analyzed the resulting gyromotions. By varying the initial parameters for the Lorentz particle tracker code, information about the different gyromotions of the test particles in the modeled Europa-Jupiter environment was deduced. For this study, we only produced and analyzed three cases for the gyromotion of energetic-charged test particles, but there are a multitude of gyromotions that can be produced by using this particle tracker code.

Chapter 4

Discussion

From this study, we developed a way to track the gyromotion of energetic-charged particles. It was found that using second order Runge-Kutta methods and the gyroperiod equation was the best method for tracking the particles in the modeled Europa-Jupiter environment. More specifically, the time resolution that produced the least error when used to track the energetic-charged test particles was 0.01 of the gyroperiod.

The algorithms we developed have the ability to track any type of energetic-charged particle; however, there were time limitations for completing our study, so we were not able to complete the suite of numerical experiments to describer the radition environment at Europa. The procedure discussed in the methodology section requires modeling various start locations and energies of the test particles in order to build up the statistics necessary to locate shielded regions at Europa. To date, we have not completed enough of these simulations to determine the location of shielded regions for the three locations of Europa relative to the plasma sheet.

As for now, the algorithms we developed can be used as a tool to track particles in a modeled Europa-Jupiter environment or any electromagnetic environment. With continued work, these algorithms will help locate shielded regions in the Europa-Jupiter environment.

The guiding force behind this research was to understand the radiation environment around Europa and its effect on spacecraft. As we continue to explore and study our outer solar system and deep space, our spacecrafts will encounter harsh environments throughout their journeys and data collection. Our study will help contribute to finding better ways to protect and increase the longevity of future missions.

References

Bagenal, F. Empirical model of the Io plasma torus: Voyager measurements. *J. geophys. Res.* **99**, 11043−11062 (1994).

Davis, Maryia. Europa Jupiter System Mission (EJSM). Outer Planet Flagship Mission. http://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/.

Fieseler, P. D. The radiation effects on Galileo spacecraft systems at Jupiter, IEEE Trans. Nucl. Sci., 49, 2739–2758 (2002).

Kivelson M.G., *et al*. Galileo Magnetometer Measurements: Stronger Case for a Subsurface Ocean at Europa, *Science* **289**, 1340 (2000).

Kliore, A. J. The ionosphere of Europa from Galileo radio occultations. *Science* **277**, 355–358 (1997).

Neubauer, F.M. The sub-Alfvénic interaction of the Galilean satellites with the Jovian magnetosphere. *J. Geophys. Res.*, **103**, 19843 (1998).

Paranicas, C. Europa's near-surface radiation environment. *geophys. Res. Letters* **34**, (2007).

Paty, C. 'Ganymede's Magnetosphere: Unraveling the Ganymede-Jupiter Interaction through Combining Multi-fluid Simulations and Observations.' PhD thesis. University of Washington, Seattle, WA. (2006).

PDS: The Planetary Data System. JPL/NASA. 2/2011. http://pds.jpl.nasa.gov/index.shtml.

Saur, J. Interaction of the Jovian magnetosphere with Europa: Constraints on the neutral atmosphere. *J. geophys. Res.* **103**, 19947−19962 (1998).